XMM search for *X*-ray emission from the black hole candidate MACHO-96-BLG-5

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ABSTRACT

MACHO-96-BLG-5 is a microlensing event observed towards the bulge of the Galaxy with exceptionally long duration of $\sim$ 970 days. The microlensing parallax fit parameters were used to estimate the lens mass $M = 6^{+10}_{-3}$ $M_{\odot}$ and its distance d which results to be in the range 0.5 kpc - 2 kpc. The upper limit on the absolute brightness for main-sequence stars of the same mass is less than 1 $L_{\odot}$ so that the lens is a good black hole candidate. If it is so, the black hole would accrete by interstellar medium thereby emitting in the X-ray band. Here, the analysis of an *XMM* deep observation towards MACHO-96-BLG-5 lens position is reported. Only an upper limit (at 99.8% confidence level) to the X-ray flux from the lens position of 9.10×10^{-15}– 1.45×10^{-14} erg cm^{-2} s^{-1} in the energy band $0.2 - 10$ keV has been obtained from that deep observation allowing to constrain the putative black hole accretion parameters.

Subject headings: black hole physics—stars:individual(MACHO-96-BLG-5)—X-ray:stars

1. Introduction

Gravitational microlensing is nowadays a well established technique to map both visible and dark matter throughout the Galaxy. The first lines of sight to be explored have been those towards the Magellanic Clouds and the bulge of the Galaxy, leading to the observation of several hundreds of microlensing events (Alcock et al. 2000 b and Sumi et al. 2006). The interpretation of the observations, although debated and controversial, supports the existence in the galactic halo of MACHOs (Massive Astrophysical Compact Halo Objects) with mass of $\simeq 0.4\ M_{\odot}$. Microlensing events towards the bulge of the Galaxy are interpreted as due to lenses prevalently belonging to the known stellar populations. However, several long-duration events towards the bulge have significant probabilities of being due to Black Hole (BH) lenses (Bennett et al. 2002 and Mao et al. 2002).

It is well known that the light curve of a typical microlensing event depends on four parameters (e.g. the mass M of the lens, the observer-lens distance d, the observer-source distance s and the lens transverse velocity $v_{\perp}$), while only two quantities are available from observations (the amplification at maximum and the event duration). Therefore, it remains a degeneracy in microlensing parameters, so that the lens mass can not be univocally determined, but only a statistical information can be obtained from the analysis of a large enough number of microlensing events.

The parameter degeneracy may be solved in a few parallax events, which are events with duration long enough to make possible to estimate d and/or $v_{\perp}$. In this case, a fit procedure to the event light curve allows to extract the value of the lens mass. This is the case of at least 22 microlensing parallax events (Poindexter et al. 2005) observed by the MACHO collaboration towards the bulge of the Galaxy. Among these events three are particularly interesting: MACHO-96-BLG-5, MACHO-98-BLG-6 and MACHO-99-BLG-22. For these three events, the lens mass has been estimated to be 6^{+10}_{-3} M$_{\odot}$, 6^{+7}_{-3} M$_{\odot}$ (Bennett et al. 2002), and 11^{+12}_{-6} M$_{\odot}$ (Mao et al. 2002; Agol et al. 2002), respectively.

The observed upper limit on the absolute brightness of these lenses is $< 1\ L_{\odot}$ so the lenses can not be stars but are most likely BHs[1] (see Bennett et al. 2002). Stellar mass BHs there exist in the Galaxy as a consequence of the evolution of massive stars, but all the candidates known up to date are members of binary systems. On the other hand, because of the shape of the microlensing light curves, we expect that the lens is an isolated object, so that the coordinates of these events give us the direction toward which pointing an X-ray instrument and acquire information on the lens nature.

Indeed, the putative BH lens may be accreting interstellar gas and could be luminous in the X-ray band if it is within the thin gas layer of the galactic disk (Mao et al. 2002). A

[1]Poindexter et al. (2005) also concluded that MACHO-99-BLG-22 is a strong BH candidate (78%), MACHO-96-BLG-5 is a marginal BH candidate (37%) and MACHO-98-BLG-6 is a weak BH candidate (2.2%).

first estimate of the X-ray flux in the 1-10 keV band leads to fluxes of $\simeq 10^{-15}$ erg cm^{-2} s^{-1} (Agol and Kamionkowski 2002).

In this paper we report on a 100 ks *XMM* observation towards the MACHO-96-BLG-5 position, in order to search for an X-ray signature from the accretion process of the BH candidate.

The paper is structured as follows: In Sect. 2, we give a short description of the gravitational lensing event MACHO-96-BLG-5 and in Sect. 4 we discuss about the X-ray observations performed towards the target by other X-ray telescopes. In Sect. 4 we report our observational results. Finally, in Sect. 5 we address some conclusion.

Before closing this section we would like to mention that detecting isolated BHs is of great importance in astrophysics since this should allow to validate or not the standard model for stellar evolution and BH formation[2]. Simple estimates indicate in fact that about 10^8 BHs should be present throughout the Galaxy (se e.g. Shapiro and Teukolsky 1983) and this is in agrement with the chemical enrichment by supernovae indicating that about 2×10^8 BHs should have formed (Samland 1998). The MACHO and OGLE groups claimed that three isolated BHs have been detected by gravitational microlensing indicating that at most $\simeq 5 \times 10^8$ $(9M_{\odot}/M_{BH})$ BHs reside in the Milky Way disk (Agol et al. 2002, Alcock et al. 2000 a). However, the number of isolated BHs present in the Galaxy should be confirmed by direct observations of their X-ray or radio emission (Maccarone 2005).

2. The gravitational lensing event MACHO-96-BLG-5

Gravitational microlensing (i.e. gravitational deflection and amplification) of electromagnetic waves is a well known phenomenon predicted by the General Theory of Relativity.

In presence of a massive object (such as a MACHO, a star or a stellar mass BH) close enough to the line of sight to a star (source), an amplification of the received flux may be observed depending on the Einstein radius $R_E = [4GMd(s-d)/(c^2 s)]^{1/2}$, d and s being the lens and source distances, respectively. Due to the relative transverse velocity $v_{\perp}$ between the lens and the line of sight to the source, the amplification is time-dependent and the duration time scale of a microlensing event is given by $\Delta T = 2R_E/v_{\perp}$.

[2]Indeed, it could be that nature has more difficulties in producing BHs than expected within the standard stellar evolution model as recently emerged by CHANDRA observation of the X-ray pulsar CXO J164710.2-455216, indicating that pulsar progenitor had mass greater than about $40M_{\odot}$ (Muno et al. 2006).

For most observed microlensing events, the lens mass can only be estimated very crudely based upon the observed time ΔT. In fact, since s is usually known and only two observed quantities (the maximum amplification and ΔT) are available from observations, it remains a degeneracy in microlensing parameters.

For long enough timescale events it is often possible to measure parallax effects which make possible to estimate the lens distance and/or its transverse velocity $v_\perp$. In this case, a fit to the event light curve allows to extract the value of the lens mass. For these events, the measurement of the projected speed of the lens allows to relate the lens mass and the source distance by

$$M \simeq \frac{v_\perp^2 \Delta T^2 c^2}{16G} \frac{1 - d/s}{d} \ , \tag{1}$$

from which it is possible to infer the lens mass once d is known.

Here, we focus on MACHO-96-BLG-5 event whose parameters are given in Table 1 (Bennett et al. 2002). MACHO-96-BLG-5 is a particularly long duration microlensing event so that parallax measurement have been performed allowing to determine the mass M of the lens as a function of the distance d (see Figure 1 where we plot the mass M as given by eq. (1) where we use the best fit parameters given in Table 1). The region between the two dashed vertical lines corresponds to the lens mass best estimate $M = 6^{+10}_{-3}$ M$_\odot$ corresponding to distances between ~ 0.5 kpc and $\sim$ 2 kpc.

3. Previous X-ray observations

An isolated BH may accrete the surrounding interstellar material as a consequence of the deep gravitational potential. It is thus expected that an X-ray emission, although weak (with respect to neutron stars of the same mass), is present. This has motivated us to search for an X-ray signature from the BH candidate in MACHO-96-BLG-5 direction.

If the BH is moving with velocity v with respect to the interstellar medium it is expected to accrete at the Bondi-Hoyle accretion rate given by (Shapiro and Teukolsky 1983, see also

Table 1: MACHO-96-BLG-5 parameters: event position in J2000 coordinates, duration, lens projected velocity and mass (Bennett et al. 2002).

RA(J2000)	DEC(J2000)	ΔT(days)	$v_\perp$(km/s)	$M(M_\odot)$
$18:05:02.5$	$-27:42:17$	970 ± 20	30.9 ± 1.3	6^{+10}_{-3}

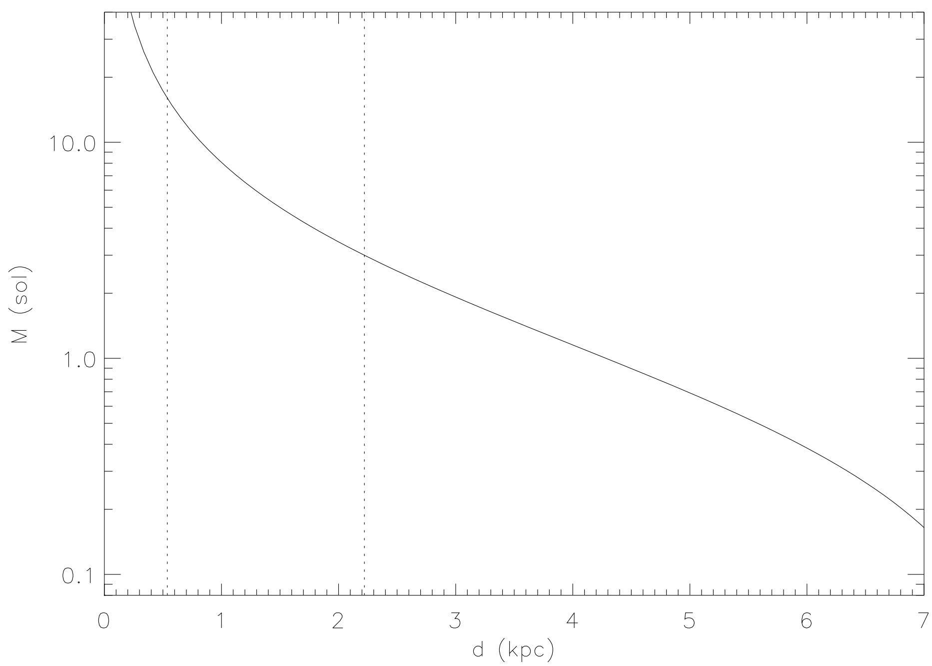

Fig. 1.— The parallax measurements allow to correlate the lens mass M to its distance d from the observer. According to the best fit parameters given in Table 1, the most plausible lens mass value is $M = 6^{+10}_{-3}$ $M_{\odot}$ corresponding to distances between ~ 0.5 and ~ 2 kpc (dashed vertical lines).

Chisholsm et al. 2003 for a more recent discussion)

$$\dot{M} = 4\pi\lambda \frac{(GM)^2}{(a_\infty^2 + v^2)^{3/2}} \rho_\infty \tag{2}$$

where λ is a constant of order unity, a_∞ is the sound velocity in the considered medium (which is in the range 0.1-10 km s^{-1}) and ρ_∞ is the interstellar medium density. Thus, the X-ray flux at Earth is

$$F_X = F_s \left(\frac{M}{M_\odot}\right)^2 \left(\frac{1\text{kpc}}{d}\right)^2 \ , \tag{3}$$

where F_s is a scale flux defined as

$$F_s = G^2 c^2 \frac{\epsilon \rho_\infty}{(a_\infty^2 + v^2)^{3/2}} \left(\frac{1 M_\odot}{1\text{kpc}}\right)^2 \ . \tag{4}$$

Assuming $\rho_\infty \simeq 8.35 \times 10^{-25}$ g cm^{-3} (corresponding to $n \simeq 0.5$ cm^{-3} as expected for the interstellar matter density) $\epsilon = 0.1$ and $v \simeq 30$ km s^{-1} (as given by the microlensing event observation), $F_s \simeq 4.45 \times 10^{-15}$ erg cm^{-2} s^{-1}.

Two observations have been carried out previously towards the MACHO-96-BLG-5 coordinates by ROSAT and CHANDRA satellites.

Maeda et al. (2005) have realized that the 9.7 ks ROSAT observation in the $0.1-2.4$ keV (Voges et al. 1999) made possible to detect 93 and 108 photons from a circular source region with a radius of 74$''$ and an annular background region with inner and outer radii of 74$''$ and 120$''$, respectively. Since the expected background counts result to be $\simeq 0.00385$ counts arcsec^{-2}, the number of background counts in the source circle is $\simeq 66$. This corresponds to a source count number as high as $\simeq 27$ corresponding to a signal-to-noise ratio of $27/\sqrt{93} \simeq 2.8$. This signal-to-noise ratio is marginally consistent with a source detection with a 2.8σ excess with a flux of $\sim 4 \times 10^{-14}$ erg cm^{-2} s^{-1} in the $0.1 - 2.4$ keV band, or $\sim 1 \times 10^{-13}$ erg cm^{-2} s^{-1} in the $0.3 - 8$ keV, where it has been assumed a photon index of 2 and an absorption column density of 3×10^{21} cm^{-2} (Maeda et al. 2005).

The X-ray signature from MACHO-96-BLG-5 has been also searched for with a 10 ks CHANDRA observation (Maeda et al. 2005). In this case, the CHANDRA ACIS-S image in the $0.3 - 8$ keV band has shown that not even a single photon was detected within 1$''$ of the target position. In addition, $\simeq 21$ counts have been detected within a circular region with 30$''$ radius centered on the MACHO-96-BLG-5 source. Hence, the background counts around the target are $\simeq 7 \times 10^{-3}$ counts arcsec^{-2}, which is consistent with the nondetection of source photons within 1$''$ from the MACHO-96-BLG-5 position. Using a simple Poissonian distribution, Maeda et al. (2005) found an upper limit of 4.6 counts at 99% confidence level and suggested that deeper observations ($\gg 10$ ks) with CHANDRA or *XMM*-Newton may detect, in principle, the weak X-ray signature from the lens of MACHO-96-BLG-5 if it is really a BH. Assuming an interstellar column density of $\simeq 3\times10^{21}$ cm^{-2}, Maeda et al. (2005) found that the previous count estimate corresponds to fluxes of 5×10^{-15} erg cm^{-2} s^{-1} and 4×10^{-15} erg cm^{-2} s^{-1}, for photon index of 1.4 and 2, respectively.

4. *XMM* Observation and Results

A 100 ks *XMM* observation towards the coordinates of MACHO-96-BLG-5 has been made on October 2005 (Observation ID 30597) with both MOS and PN cameras operating with thin filter mode.

The Epic Observation Data File (ODFs) where processed using the *XMM*-Science Analysis System (SAS version 6.5.0). With the latest calibration constituent files available in 2006 May, we have processed the raw data with the *emchain* and *epchain* tools to generate proper event list files. We then only considered events with patterns $0-12$ (resp. $0-4$) for the MOS (resp. PN) instruments and we applied the filtering criterion XMMEA_EM (resp. FLAG== 0) as recommended by the Science Operation Centre (SOC) technical note XMM-PS-TN-43 v3.0. We have used the *evselect* tool in order to extract light curves and images from the data. For our pointing, we have rejected time periods affected by soft protons flares which are evident, in the extracted light curves, as spikes. For this purpose, we built light curves for the MOS and PN instruments at energies above 10 keV (in particular in the energy band 10 keV - 12 keV) where the effect of soft protons flares is more evident. These data were recursively cleaned by removing all bins with counts larger than 3σ from the mean. New mean and new deviation are then found and the entire process has been repeated until a mean count rate per bin is reached. This procedure, when applied to MOS and PN data, allowed us to discard high background observing periods on the basis of the derived thresholds of 22.5 counts (or 0.225 counts sec^{-1}) for MOS 1, 26.0 counts (or 0.26 counts sec^{-1}) for MOS 2 and 49.04 counts (or 0.490 counts sec^{-1}) for PN, respectively. Hence, with the *tabgtigen* tool, Good Time Intervals (GTIs) were obtained and used in order to produce adequate X-ray event lists for each instruments. The remaining good time intervals added up resulting in effective exposures of $\simeq 95$ ks, $\simeq 98$ ks and $\simeq 67$ ks for MOS 1, MOS 2 and PN, respectively.

In Figure 2, we show the full *XMM* field of view (as a composite image of the MOS 1, MOS 2 and PN images in the $0.2-10$ keV band) towards the MACHO-96-BLG-5 region. The deep exposure has shown the existence of several new X-ray sources (not seen in previous X-ray observations) which will be investigated elsewhere. In Figure 3, we show an enlargement of the previous figure around the coordinates of the MACHO-96-BLG-5 target. In particular, the circle with radius $\simeq 15''$ (each pixel size is $\simeq 5''$) is centered on the target coordinates given in Table 1. As it is evident from Figure 3, if a X-ray source exists in the encircled region it has to be extremely weak. In the following, we will quantify this conclusion.

In order to confirm the absolute astrometry of our observations, we searched for counterparts of the putative X-ray sources in the Tycho-2 optical astrometric catalogue (Hog et al. 2000), and we have found a number of objects (whose coordinates are given in Table 2) corresponding to X-ray sources present in the *XMM* field of view.

MOS 1, MOS 2 and PN images were produced in the $0.2-10$ keV band with a binning that resulted in pixels of $5''$, close to the full width at half maximum of the point spread function of the EPIC instruments. None of the images showed an apparent excess in photons at the location of the source. Images in narrower energy bands across the $0.2-10$ keV range (i.e. 0.2-0.5 keV, 0.5-2 keV, 2-4.5 keV, 4.5-7 keV and 7-10 keV) were also produced but they did not show an obvious source detection either.

We may also exclude the possibility that, as a consequence of the proper motion, the BH candidate has moved away from its original position. This possibility can be easily ruled out since, for a lens distance in the range 0.5 kpc–2 kpc (see Figure 1), as deduced by the parallax measurement of the MACHO-96-BLG-5 microlensing event, and for a conservative relative velocity between the lens and the observer of $\simeq 30$ km s^{-1}, the lens has moved from its original position at most of $\simeq 0.015'' - 0.12''$ in a period of 10 years. Hence, because of the *XMM* pixel size quoted above, such a motion is completely negligible in our case.

Next, we ran the *edetect_chain* simultaneously on the three images (MOS 1, MOS 2 and PN in the 0.2-10 keV band) produced. The subtask *eboxdetect* was used with a detection threshold of *likemin=8* to provide a complete source list as input for subsequent tasks. No source was detected at the position of MACHO-96-BLG-5. As suggested by the *User's Guide to the XMM-Newton Science Analysis System* (Loiseau 2004), especially in cases where an expected X-ray source is not detected by the usual source detection tasks, we have used the *esenmap* command to generate a sensitivity map roughly giving point source detection upper limit (in units of counts s^{-1}). Performing this task on the MOS 1, MOS 2 and PN images in the 0.2-10 keV band, we obtained the rates of 3.1×10^{-4} count s^{-1}, 3.0×10^{-4} count s^{-1} and 6.2×10^{-4} count s^{-1}, respectively [3].

[3] As a comparison, the weakest source detected with the automatic procedure has a cumulative count rate of 1.7×10^{-3} count s^{-1} (2.2×10^{-4} count s^{-1} for MOS 1, 5.4×10^{-4} count s^{-1} for MOS 2 and 9.3×10^{-4} count s^{-1} for PN, respectively).

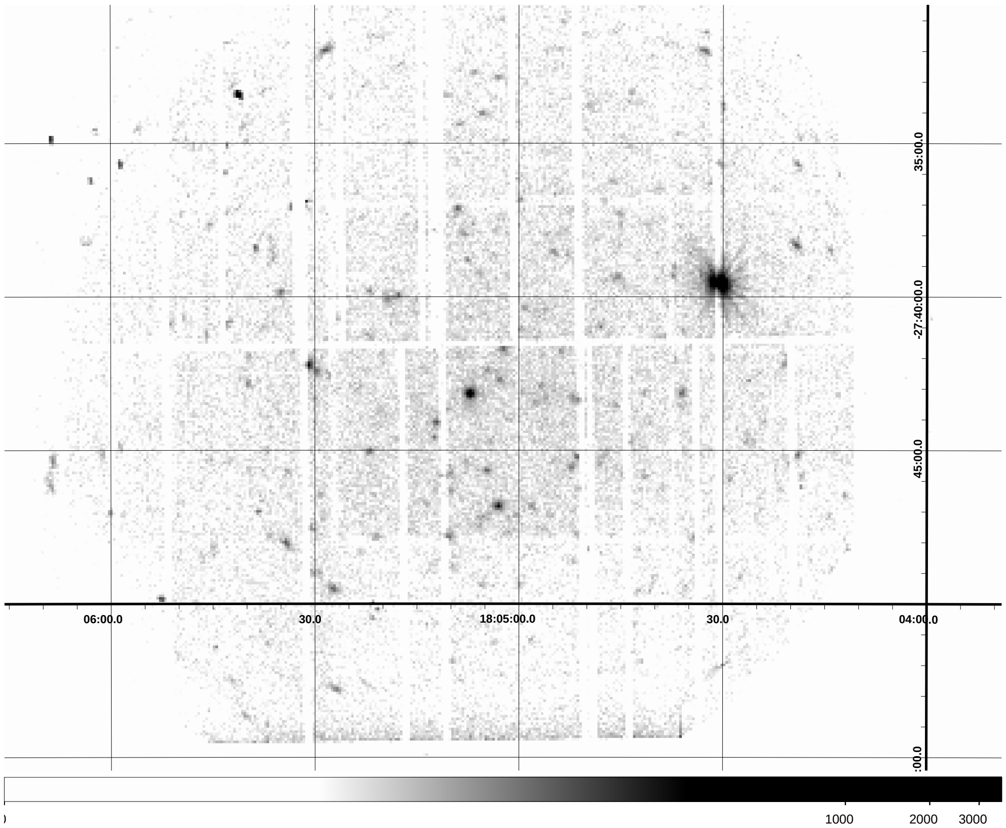

Fig. 2.— The deep *XMM* exposure has shown the existence of a number of new *X*-ray sources which will be investigated elsewhere.

Table 2. A list of optical sources (from Tycho-2 optical astrometric catalogue) whose coordinates correspond to *X*-ray sources in our image is given.

	α (2000)			δ (2000)			V mag
Source ID	h	m	s	$^\circ$	$'$	$''$	
1	18	5	30.75	-27	42	12.790	11.460
2	18	5	21.61	-27	29	40.50	11.163
3	18	5	40.08	-27	53	38.20	10.160
4	18	4	41.95	-27	30	35.60	12.141
5	18	5	3.55	-27	33	30.61	10.925
6	18	5	31.94	-27	54	36.17	11.244

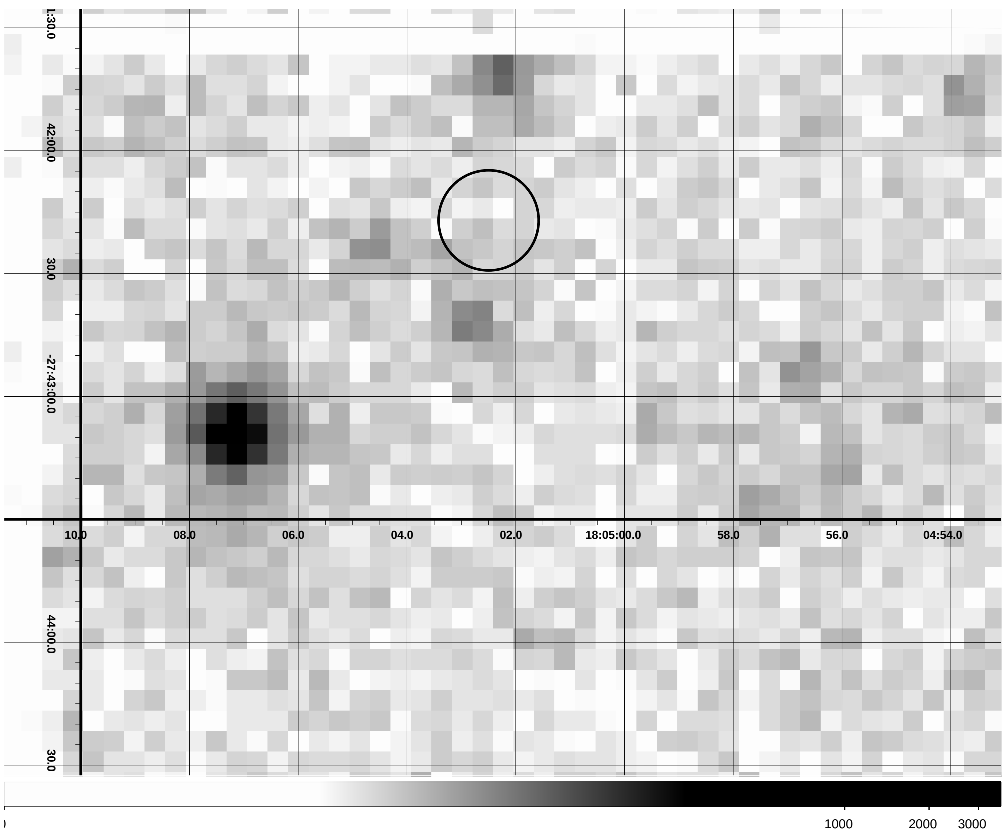

Fig. 3.— An enlargement of the *XMM* exposure around the coordinates of the MACHO-96-BLG-5 target is shown. In particular, the circle with radius $\simeq 15''$ (each pixel size is $\simeq 5''$) is centered on the target coordinates given in Table 1.

The X-ray rate from MACHO-96-BLG-5 in the $0.2 - 10$ keV band can be determined in the following alternative way. We consider a source extraction region around the target coordinates and several background extraction regions sufficiently far from any bright point source but on the same chip where our target is supposed to be. Let us assume that the source and background extraction regions have circular shape with the radii R_s and R_b and covering area A_s and A_b, respectively. For the source extraction region we fixed $R_s = 2.45$ pixels (or equivalently 12.5 arcsec) so that it is collected at least 65% (resp. 60%) of the encircled energy when the MOS (resp. PN) instrument is used. In the case of the background extraction region a radius $R_b = 10$ pixels (resp. $R_b = 6$ pixels) has been chosen for MOS 1 and MOS 2 (resp. PN). Therefore, the covering areas are $A_s \simeq 475$ arcsec^2 and $A_b \simeq 7775$ arcsec^2 for MOS 1 and MOS 2 and $A_b \simeq 2735$ arcsec^2 for PN, respectively. We also emphasize that the source extraction region has been chosen to be smaller than the background extraction region to avoid strong contamination by nearby sources.

Let N_{s+b} and N_b be the numbers of counts expected within the source and background regions, respectively. We assume that within the source circle, the observed count number depends on the properties of both the source and background, while the counts eventually observed within the background region are due to background only. In this case the number of counts due to the source is

$$N_s = N_{s+b} - \frac{A_s}{A_b} N_b \ . \tag{5}$$

We tested different choices of background region positions, until we were satisfied that the contaminations due to close sources were properly subtracted. The number of counts detected within the circle (with radius R_s) centered on the nominal source position were 60, 73 and 252 in the MOS 1, MOS 2 and PN cameras, respectively. Using the tables in (Gehrels 1986), this leads to single-sided 3σ (or 99.8%) upper limits of 87.1, 102.5 and 303.4 on the total counts. The expected background counts (after correcting for exposure map differences and rescaling for the extraction area) are 56, 64 and 227 for MOS 1, MOS 2 and PN, respectively. Correcting for the background, one has 31.1, 38.5 and 76.4 counts corresponding to the rates of 3.2×10^{-4} count s^{-1}, 3.9×10^{-4} count s^{-1} and 1.0×10^{-3} count s^{-1}, respectively.

We have also evaluated the expected 0.2-10 keV flux upper limit using PIMMS. For this reason, we have assumed an interstellar absorbtion column density of 3.81×10^{21} cm^{-2} (as estimated by the Nh Heasarc Tool) and a power law spectrum with indices Γ varying in the range 1.5 and 2.5. For the MOS 1 instrument the previously quoted count rates correspond to unabsorbed fluxes of 9.10×10^{-15} erg cm^{-2} s^{-1} ($\Gamma = 1.5$) and 1.20×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 2.5$). For the MOS 2 instrument we get the unabsorbed fluxes of 1.12×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 1.5$) and 1.45×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 2.5$). For EPIC-PN we find 1.03×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 1.5$) and 1.28×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 2.5$), respectively. Therefore, we can set an upper limit for the flux from the putative source in the range 9.10×10^{-15}–1.45×10^{-14} erg cm^{-2} s^{-1}.

5. Discussion and conclusions

MACHO-96-BLG-5 is a microlensing observed event towards the bulge of the Galaxy with the exceptionally long duration of $\sim$ 970 days[4]. The measure of the parallax angle (Bennett et al. 2002) made it possible to estimate both the lens mass ($M = 6^{+10}_{-3}$ M$_{\odot}$) and its distance d from Earth (0.5–2 kpc).

Since the observed upper limits on the absolute brightness of main-sequence stars for this lens is $< 1\ L_{\odot}$, MACHO-96-BLG-5 is a BH candidate. If it is so, then the BH would accrete by interstellar medium (via the Bondi-Hoyle mechanism) thereby emitting X rays. Here, we have reported about a deep *XMM* observation in the $0.2 - 10$ keV band towards MACHO-96-BLG-5 lens position. The analysis of the observations (see Section 4) did not show any obvious source and it is consistent with a non-detection of the source. However, it is possible to estimate an upper limit on the source luminosity, which turns out to be in the range 9.10×10^{-15}– 1.45×10^{-14} erg cm^{-2} s^{-1}, depending on the power law index Γ.

This upper limit allows to constrain the accretion parameters of the BH candidate from a parametric study involving eqs. (3) and (4). In the BH mass-distance plane given in Figure 4, the curved line corresponds to the mass-distance relation (also given in Figure 1). This means that our BH candidate should lie on this curve (if its transverse velocity is $\simeq 30$ km s^{-1}) and within the two dotted vertical lines. The three oblique lines correspond to the X-ray upper limit of 9.10×10^{-15} erg cm^{-2} s^{-1} for three different values of the scale flux (F_s, $10^{-1}F_s$ and $10^{-2}F_s$). Obviously, varying F_s, it means that the accretion parameters (ϵ, ρ_{∞} and v) are changing. Thus, the region below the line labeled F_s corresponds to $F_X < 9.10 \times 10^{-15}$ erg cm^{-2} s^{-1}. The same holds for the regions below the other two lines. It is noticing that a BH accreting with $\rho_{\infty} \simeq 8.35 \times 10^{-25}$ g cm^{-3}, $\epsilon = 0.1$ and $v \simeq 30$ km s^{-1} (implying $F_s \simeq 4.45 \times 10^{-15}$ erg cm^{-2} s^{-1}), is inconsistent with the best fit values (mass and distance) for the MACHO-96-BLG-5 lens candidate. However, for a less efficient Bondi accretion ($\epsilon \simeq 10^{-5} - 10^{-3}$) the regions below the other two oblique lines show that the agreement is recovered.

[4] We also mention that recently Poindexter et al. (2005) presented the best fit solution for geocentric timescale for the same microlensing event and found that the event duration is 546 ± 165 days or 698 ± 303 days. This analysis leads to the conclusion that the lens of MACHO-96-BLG-5 is BH with a probability of about 37%.

Finally, it could be interesting to estimate the BH radiative efficiency $\eta = L_X/L_{Edd}$ with respect to the maximum allowed BH accretion rate given by the Eddington luminosity $L_{Edd} \simeq 1.38 \times 10^{38}(M/M_\odot)$ erg s^{-1}. By using the BH mass and distance ranges, namely $3 < M < 16$ M$_\odot$ and $0.5 < d < 2$ kpc, we can compare the Eddington luminosity with the X-ray luminosity given by $L_X = F_X 4\pi d^2$ expected for MACHO-96-BLG-5. This procedure gives η in the range $1.2\times10^{-10} - 2.7\times10^{-9}$, in agreement with the efficiency estimates for BH accretion in quiescent galaxies and ultra-low luminous AGNs for which $\eta = 4\times10^{-12}$- 6×10^{-7} (Baganoff et al. 2003).

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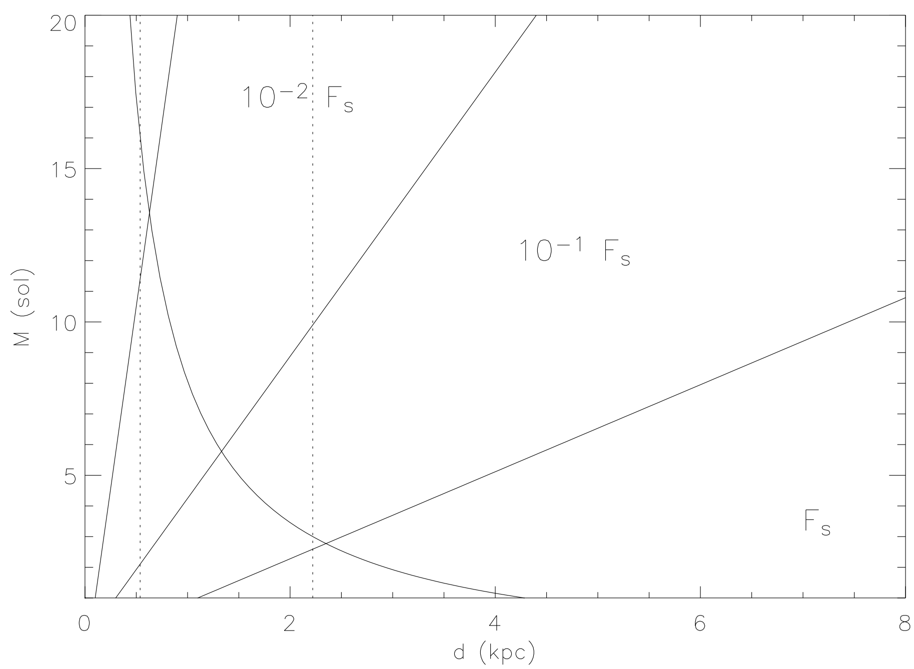

Fig. 4.— In the mass-distance plane (see Figure 1), the three oblique lines define the regions (below each line) where the X-ray flux due to the Bondi accretion is below the upper limit flux of 9.10×10^{-15} erg cm^{-2} s^{-1}.

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An *XMM* search for *X*-ray emission from the microlensing event MACHO-96-BLG-5

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ABSTRACT

MACHO-96-BLG-5 is a microlensing event observed towards the bulge of the Galaxy with exceptionally long duration of $\sim$ 970 days. The microlensing parallax fit parameters were used to estimate the lens mass $M = 6^{+10}_{-3}$ $M_{\odot}$ and its distance d which results to be in the range 0.5 kpc - 2 kpc. The upper limit on the absolute brightness for main-sequence stars of the same mass is less than 1 $L_{\odot}$ so that the lens is a good black hole candidate. If it is so, the black hole would accrete by interstellar medium thereby emitting in the X-ray band. Here, the analysis of an *XMM* deep observation towards MACHO-96-BLG-5 lens position is reported. Only an upper limit (at 99.8% confidence level) to the X-ray flux from the lens position of 9.10×10^{-15}– 1.45×10^{-14} erg cm^{-2} s^{-1} in the energy band $0.2 - 10$ keV has been obtained from that deep observation allowing to constrain the putative black hole accretion parameters.

Subject headings: black hole physics—stars:individual(MACHO-96-BLG-5)—X-ray:stars

1. Introduction

Gravitational microlensing is nowadays a well established technique to map both visible and dark matter throughout the Galaxy. The first lines of sight to be explored have been those towards the Magellanic Clouds and the bulge of the Galaxy, leading to the observation of several hundreds of microlensing events (Alcock et al. 2000 b and Sumi et al. 2006). The interpretation of the observations, although debated and controversial, supports the existence in the galactic halo of MACHOs (Massive Astrophysical Compact Halo Objects) with mass of $\simeq 0.4\ M_\odot$. Microlensing events towards the bulge of the Galaxy are interpreted as due to lenses prevalently belonging to the known stellar populations. However, several long-duration events towards the bulge have significant probabilities of being due to Black Hole (BH) lenses (Bennett et al. 2002 and Mao et al. 2002).

It is well known that the light curve of a typical microlensing event depends on four parameters (e.g. the mass M of the lens, the observer-lens distance d, the observer-source distance s and the lens transverse velocity $v_\perp$), while only two quantities are available from observations (the amplification at maximum and the event duration). Therefore, it remains a degeneracy in microlensing parameters, so that the lens mass can not be univocally determined, but only a statistical information can be obtained from the analysis of a large enough number of microlensing events.

The parameter degeneracy may be solved in a few parallax events, which are events with duration long enough to make possible to estimate d and/or $v_\perp$. In this case, a fit procedure to the event light curve allows to extract the value of the lens mass. This is the case of at least 22 microlensing parallax events (Poindexter et al. 2005) observed by the MACHO collaboration towards the bulge of the Galaxy. Among these events three are particularly interesting: MACHO-96-BLG-5, MACHO-98-BLG-6 and MACHO-99-BLG-22. For these three events, the lens mass has been estimated to be 6^{+10}_{-3} M$_\odot$, 6^{+7}_{-3} M$_\odot$ (Bennett et al. 2002), and 11^{+12}_{-6} M$_\odot$ (Mao et al. 2002; Agol et al. 2002), respectively.

The observed upper limit on the absolute brightness of these lenses is $< 1\ L_\odot$ so the lenses can not be stars but are most likely BHs[1] (see Bennett et al. 2002). Stellar mass BHs there exist in the Galaxy as a consequence of the evolution of massive stars, but all the candidates known up to date are members of binary systems. On the other hand, because of the shape of the microlensing light curves, we expect that the lens is an isolated object, so that the coordinates of these events give us the direction toward which pointing an X-ray instrument and acquire information on the lens nature.

Indeed, the putative BH lens may be accreting interstellar gas and could be luminous in the X-ray band if it is within the thin gas layer of the galactic disk (Mao et al. 2002). A

[1]Poindexter et al. (2005) also concluded that MACHO-99-BLG-22 is a strong BH candidate (78%), MACHO-96-BLG-5 is a marginal BH candidate (37%) and MACHO-98-BLG-6 is a weak BH candidate (2.2%).

first estimate of the X-ray flux in the 1-10 keV band leads to fluxes of $\simeq 10^{-15}$ erg cm^{-2} s^{-1} (Agol and Kamionkowski 2002).

In this paper we report on a 100 ks *XMM* observation towards the MACHO-96-BLG-5 position, in order to search for an X-ray signature from the accretion process of the BH candidate.

The paper is structured as follows: In Sect. 2, we give a short description of the gravitational lensing event MACHO-96-BLG-5 and in Sect. 4 we discuss about the X-ray observations performed towards the target by other X-ray telescopes. In Sect. 4 we report our observational results. Finally, in Sect. 5 we address some conclusion.

Before closing this section we would like to mention that detecting isolated BHs is of great importance in astrophysics since this should allow to validate or not the standard model for stellar evolution and BH formation[2]. Simple estimates indicate in fact that about 10^8 BHs should be present throughout the Galaxy (se e.g. Shapiro and Teukolsky 1983) and this is in agrement with the chemical enrichment by supernovae indicating that about 2×10^8 BHs should have formed (Samland 1998). The MACHO and OGLE groups claimed that three isolated BHs have been detected by gravitational microlensing indicating that at most $\simeq 5 \times 10^8$ $(9M_\odot/M_{BH})$ BHs reside in the Milky Way disk (Agol et al. 2002, Alcock et al. 2000 a). However, the number of isolated BHs present in the Galaxy should be confirmed by direct observations of their X-ray or radio emission (Maccarone 2005).

2. The gravitational lensing event MACHO-96-BLG-5

Gravitational microlensing (i.e. gravitational deflection and amplification) of electromagnetic waves is a well known phenomenon predicted by the General Theory of Relativity.

In presence of a massive object (such as a MACHO, a star or a stellar mass BH) close enough to the line of sight to a star (source), an amplification of the received flux may be observed depending on the Einstein radius $R_E = [4GMd(s-d)/(c^2 s)]^{1/2}$, d and s being the lens and source distances, respectively. Due to the relative transverse velocity $v_\perp$ between the lens and the line of sight to the source, the amplification is time-dependent and the duration time scale of a microlensing event is given by $\Delta T = 2R_E/v_\perp$.

[2]Indeed, it could be that nature has more difficulties in producing BHs than expected within the standard stellar evolution model as recently emerged by CHANDRA observation of the X-ray pulsar CXO J164710.2-455216, indicating that pulsar progenitor had mass greater than about $40M_\odot$ (Muno et al. 2006).

For most observed microlensing events, the lens mass can only be estimated very crudely based upon the observed time ΔT. In fact, since s is usually known and only two observed quantities (the maximum amplification and ΔT) are available from observations, it remains a degeneracy in microlensing parameters.

For long enough timescale events it is often possible to measure parallax effects which make possible to estimate the lens distance and/or its transverse velocity $v_\perp$. In this case, a fit to the event light curve allows to extract the value of the lens mass. For these events, the measurement of the projected speed of the lens allows to relate the lens mass and the source distance by

$$M \simeq \frac{v_\perp^2 \Delta T^2 c^2}{16G} \frac{1 - d/s}{d} , \quad (1)$$

from which it is possible to infer the lens mass once d is known.

Here, we focus on MACHO-96-BLG-5 event whose parameters are given in Table 1 (Bennett et al. 2002). MACHO-96-BLG-5 is a particularly long duration microlensing event so that parallax measurement have been performed allowing to determine the mass M of the lens as a function of the distance d (see Figure 1 where we plot the mass M as given by eq. (1) where we use the best fit parameters given in Table 1). The region between the two dashed vertical lines corresponds to the lens mass best estimate $M = 6^{+10}_{-3}$ M$_\odot$ corresponding to distances between ~ 0.5 kpc and $\sim$ 2 kpc.

3. Previous X-ray observations

An isolated BH may accrete the surrounding interstellar material as a consequence of the deep gravitational potential. It is thus expected that an X-ray emission, although weak (with respect to neutron stars of the same mass), is present. This has motivated us to search for an X-ray signature from the BH candidate in MACHO-96-BLG-5 direction.

If the BH is moving with velocity v with respect to the interstellar medium it is expected to accrete at the Bondi-Hoyle accretion rate given by (Shapiro and Teukolsky 1983, see also

Table 1: MACHO-96-BLG-5 parameters: event position in J2000 coordinates, duration, lens projected velocity and mass (Bennett et al. 2002).

RA(J2000)	DEC(J2000)	ΔT(days)	$v_\perp$(km/s)	$M(M_\odot)$
$18:05:02.5$	$-27:42:17$	970 ± 20	30.9 ± 1.3	6^{+10}_{-3}

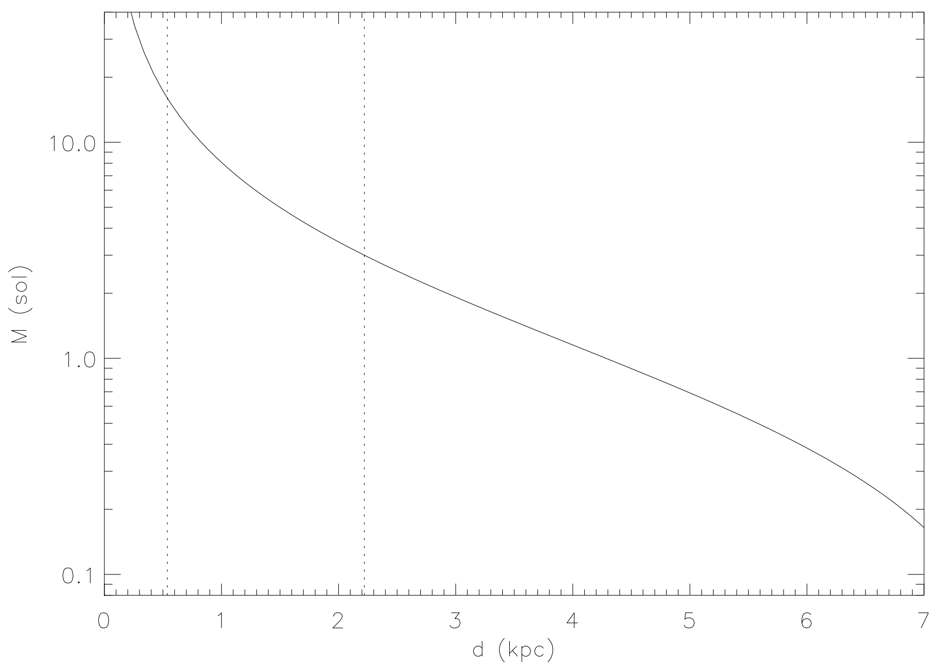

Fig. 1.— The parallax measurements allow to correlate the lens mass M to its distance d from the observer. According to the best fit parameters given in Table 1, the most plausible lens mass value is $M = 6^{+10}_{-3}$ $M_\odot$ corresponding to distances between $\sim$ 0.5 and $\sim$ 2 kpc (dashed vertical lines).

Chisholsm et al. 2003 for a more recent discussion)

$$\dot{M} = 4\pi\lambda \frac{(GM)^2}{(a_\infty^2 + v^2)^{3/2}} \rho_\infty \tag{2}$$

where λ is a constant of order unity, a_∞ is the sound velocity in the considered medium (which is in the range 0.1-10 km s^{-1}) and ρ_∞ is the interstellar medium density. Thus, the X-ray flux at Earth is

$$F_X = F_s \left(\frac{M}{M_\odot}\right)^2 \left(\frac{1\mathrm{kpc}}{d}\right)^2 , \tag{3}$$

where F_s is a scale flux defined as

$$F_s = G^2 c^2 \frac{\epsilon \rho_\infty}{(a_\infty^2 + v^2)^{3/2}} \left(\frac{1M_\odot}{1\mathrm{kpc}}\right)^2 . \tag{4}$$

Assuming $\rho_\infty \simeq 8.35 \times 10^{-25}$ g cm^{-3} (corresponding to $n \simeq 0.5$ cm^{-3} as expected for the interstellar matter density) $\epsilon = 0.1$ and $v \simeq 30$ km s^{-1} (as given by the microlensing event observation), $F_s \simeq 4.45 \times 10^{-15}$ erg cm^{-2} s^{-1}.

Two observations have been carried out previously towards the MACHO-96-BLG-5 coordinates by ROSAT and CHANDRA satellites.

Maeda et al. (2005) have realized that the 9.7 ks ROSAT observation in the $0.1-2.4$ keV (Voges et al. 1999) made possible to detect 93 and 108 photons from a circular source region with a radius of 74″ and an annular background region with inner and outer radii of 74″ and 120″, respectively. Since the expected background counts result to be $\simeq 0.00385$ counts arcsec^{-2}, the number of background counts in the source circle is $\simeq 66$. This corresponds to a source count number as high as $\simeq 27$ corresponding to a signal-to-noise ratio of $27/\sqrt{93} \simeq 2.8$. This signal-to-noise ratio is marginally consistent with a source detection with a 2.8σ excess with a flux of $\sim 4 \times 10^{-14}$ erg cm^{-2} s^{-1} in the $0.1 - 2.4$ keV band, or $\sim 1 \times 10^{-13}$ erg cm^{-2} s^{-1} in the $0.3 - 8$ keV, where it has been assumed a photon index of 2 and an absorption column density of 3×10^{21} cm^{-2} (Maeda et al. 2005).

The X-ray signature from MACHO-96-BLG-5 has been also searched for with a 10 ks CHANDRA observation (Maeda et al. 2005). In this case, the CHANDRA ACIS-S image in the $0.3 - 8$ keV band has shown that not even a single photon was detected within 1″ of the target position. In addition, $\simeq 21$ counts have been detected within a circular region with 30″ radius centered on the MACHO-96-BLG-5 source. Hence, the background counts around the target are $\simeq 7 \times 10^{-3}$ counts arcsec^{-2}, which is consistent with the nondetection of source photons within 1″ from the MACHO-96-BLG-5 position. Using a simple Poissonian distribution, Maeda et al. (2005) found an upper limit of 4.6 counts at 99% confidence level and suggested that deeper observations ($\gg 10$ ks) with CHANDRA or *XMM*-Newton may detect, in principle, the weak X-ray signature from the lens of MACHO-96-BLG-5 if it is really a BH. Assuming an interstellar column density of $\simeq 3\times10^{21}$ cm^{-2}, Maeda et al. (2005) found that the previous count estimate corresponds to fluxes of 5×10^{-15} erg cm^{-2} s^{-1} and 4×10^{-15} erg cm^{-2} s^{-1}, for photon index of 1.4 and 2, respectively.

4. *XMM* Observation and Results

A 100 ks *XMM* observation towards the coordinates of MACHO-96-BLG-5 has been made on October 2005 (Observation ID 30597) with both MOS and PN cameras operating with thin filter mode.

The Epic Observation Data File (ODFs) where processed using the *XMM*-Science Analysis System (SAS version 6.5.0). With the latest calibration constituent files available in 2006 May, we have processed the raw data with the *emchain* and *epchain* tools to generate proper event list files. We then only considered events with patterns $0-12$ (resp. $0-4$) for the MOS (resp. PN) instruments and we applied the filtering criterion XMMEA_EM (resp. FLAG== 0) as recommended by the Science Operation Centre (SOC) technical note XMM-PS-TN-43 v3.0. We have used the *evselect* tool in order to extract light curves and images from the data. For our pointing, we have rejected time periods affected by soft protons flares which are evident, in the extracted light curves, as spikes. For this purpose, we built light curves for the MOS and PN instruments at energies above 10 keV (in particular in the energy band 10 keV - 12 keV) where the effect of soft protons flares is more evident. These data were recursively cleaned by removing all bins with counts larger than 3σ from the mean. New mean and new deviation are then found and the entire process has been repeated until a mean count rate per bin is reached. This procedure, when applied to MOS and PN data, allowed us to discard high background observing periods on the basis of the derived thresholds of 22.5 counts (or 0.225 counts sec^{-1}) for MOS 1, 26.0 counts (or 0.26 counts sec^{-1}) for MOS 2 and 49.04 counts (or 0.490 counts sec^{-1}) for PN, respectively. Hence, with the *tabgtigen* tool, Good Time Intervals (GTIs) were obtained and used in order to produce adequate X-ray event lists for each instruments. The remaining good time intervals added up resulting in effective exposures of $\simeq 95$ ks, $\simeq 98$ ks and $\simeq 67$ ks for MOS 1, MOS 2 and PN, respectively.

In Figure 2, we show the full *XMM* field of view (as a composite image of the MOS 1, MOS 2 and PN images in the $0.2-10$ keV band) towards the MACHO-96-BLG-5 region. The deep exposure has shown the existence of several new X-ray sources (not seen in previous X-ray observations) which will be investigated elsewhere. In Figure 3, we show an enlargement of the previous figure around the coordinates of the MACHO-96-BLG-5 target. In particular, the circle with radius $\simeq 15''$ (each pixel size is $\simeq 5''$) is centered on the target coordinates given in Table 1. As it is evident from Figure 3, if a X-ray source exists in the encircled region it has to be extremely weak. In the following, we will quantify this conclusion.

In order to confirm the absolute astrometry of our observations, we searched for counterparts of the putative X-ray sources in the Tycho-2 optical astrometric catalogue (Hog et al. 2000), and we have found a number of objects (whose coordinates are given in Table 2) corresponding to X-ray sources present in the *XMM* field of view.

MOS 1, MOS 2 and PN images were produced in the $0.2-10$ keV band with a binning that resulted in pixels of $5''$, close to the full width at half maximum of the point spread function of the EPIC instruments. None of the images showed an apparent excess in photons at the location of the source. Images in narrower energy bands across the $0.2-10$ keV range (i.e. 0.2-0.5 keV, 0.5-2 keV, 2-4.5 keV, 4.5-7 keV and 7-10 keV) were also produced but they did not show an obvious source detection either.

We may also exclude the possibility that, as a consequence of the proper motion, the BH candidate has moved away from its original position. This possibility can be easily ruled out since, for a lens distance in the range 0.5 kpc–2 kpc (see Figure 1), as deduced by the parallax measurement of the MACHO-96-BLG-5 microlensing event, and for a conservative relative velocity between the lens and the observer of $\simeq 30$ km s^{-1}, the lens has moved from its original position at most of $\simeq 0.015'' - 0.12''$ in a period of 10 years. Hence, because of the *XMM* pixel size quoted above, such a motion is completely negligible in our case.

Next, we ran the *edetect_chain* simultaneously on the three images (MOS 1, MOS 2 and PN in the 0.2-10 keV band) produced. The subtask *eboxdetect* was used with a detection threshold of *likemin=8* to provide a complete source list as input for subsequent tasks. No source was detected at the position of MACHO-96-BLG-5. As suggested by the *User's Guide to the XMM-Newton Science Analysis System* (Loiseau 2004), especially in cases where an expected X-ray source is not detected by the usual source detection tasks, we have used the *esenmap* command to generate a sensitivity map roughly giving point source detection upper limit (in units of counts s^{-1}). Performing this task on the MOS 1, MOS 2 and PN images in the 0.2-10 keV band, we obtained the rates of 3.1×10^{-4} count s^{-1}, 3.0×10^{-4} count s^{-1} and 6.2×10^{-4} count s^{-1}, respectively [3].

[3] As a comparison, the weakest source detected with the automatic procedure has a cumulative count rate of 1.7×10^{-3} count s^{-1} (2.2×10^{-4} count s^{-1} for MOS 1, 5.4×10^{-4} count s^{-1} for MOS 2 and 9.3×10^{-4} count s^{-1} for PN, respectively).

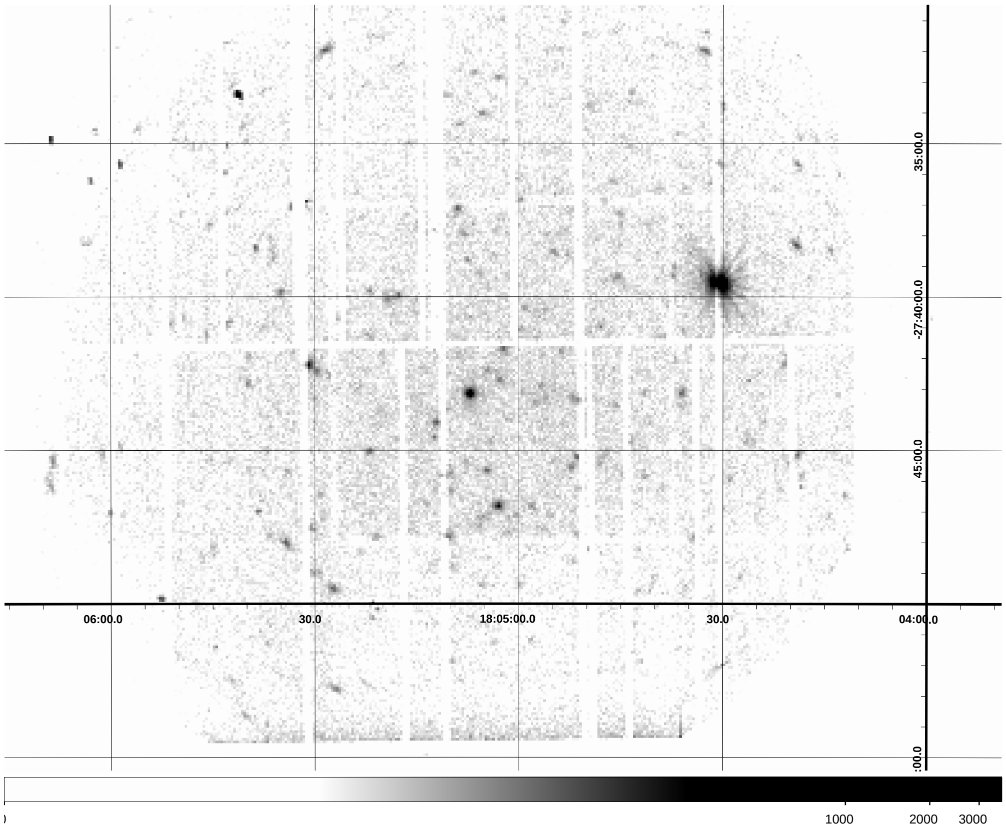

Fig. 2.— The deep *XMM* exposure has shown the existence of a number of new X-ray sources which will be investigated elsewhere.

Table 2. A list of optical sources (from Tycho-2 optical astrometric catalogue) whose coordinates correspond to X-ray sources in our image is given.

	α (2000)			δ (2000)			V mag
Source ID	h	m	s	$\circ$	$'$	$''$	
1	18	5	30.75	-27	42	12.790	11.460
2	18	5	21.61	-27	29	40.50	11.163
3	18	5	40.08	-27	53	38.20	10.160
4	18	4	41.95	-27	30	35.60	12.141
5	18	5	3.55	-27	33	30.61	10.925
6	18	5	31.94	-27	54	36.17	11.244

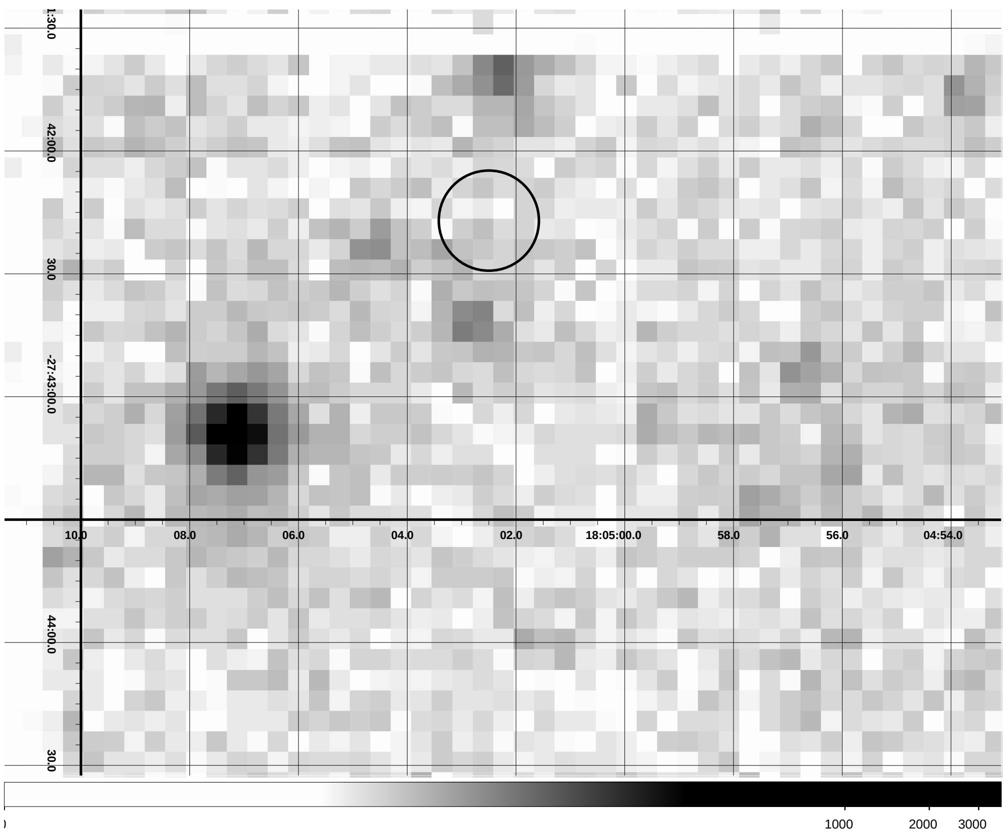

Fig. 3.— An enlargement of the *XMM* exposure around the coordinates of the MACHO-96-BLG-5 target is shown. In particular, the circle with radius $\simeq 15''$ (each pixel size is $\simeq 5''$) is centered on the target coordinates given in Table 1.

The X-ray rate from MACHO-96-BLG-5 in the $0.2 - 10$ keV band can be determined in the following alternative way. We consider a source extraction region around the target coordinates and several background extraction regions sufficiently far from any bright point source but on the same chip where our target is supposed to be. Let us assume that the source and background extraction regions have circular shape with the radii R_s and R_b and covering area A_s and A_b, respectively. For the source extraction region we fixed $R_s = 2.45$ pixels (or equivalently 12.5 arcsec) so that it is collected at least 65% (resp. 60%) of the encircled energy when the MOS (resp. PN) instrument is used. In the case of the background extraction region a radius $R_b = 10$ pixels (resp. $R_b = 6$ pixels) has been chosen for MOS 1 and MOS 2 (resp. PN). Therefore, the covering areas are $A_s \simeq 475$ arcsec^2 and $A_b \simeq 7775$ arcsec^2 for MOS 1 and MOS 2 and $A_b \simeq 2735$ arcsec^2 for PN, respectively. We also emphasize that the source extraction region has been chosen to be smaller than the background extraction region to avoid strong contamination by nearby sources.

Let N_{s+b} and N_b be the numbers of counts expected within the source and background regions, respectively. We assume that within the source circle, the observed count number depends on the properties of both the source and background, while the counts eventually observed within the background region are due to background only. In this case the number of counts due to the source is

$$N_s = N_{s+b} - \frac{A_s}{A_b} N_b \ . \tag{5}$$

We tested different choices of background region positions, until we were satisfied that the contaminations due to close sources were properly subtracted. The number of counts detected within the circle (with radius R_s) centered on the nominal source position were 60, 73 and 252 in the MOS 1, MOS 2 and PN cameras, respectively. Using the tables in (Gehrels 1986), this leads to single-sided 3σ (or 99.8%) upper limits of 87.1, 102.5 and 303.4 on the total counts. The expected background counts (after correcting for exposure map differences and rescaling for the extraction area) are 56, 64 and 227 for MOS 1, MOS 2 and PN, respectively. Correcting for the background, one has 31.1, 38.5 and 76.4 counts corresponding to the rates of 3.2×10^{-4} count s^{-1}, 3.9×10^{-4} count s^{-1} and 1.0×10^{-3} count s^{-1}, respectively.

We have also evaluated the expected 0.2-10 keV flux upper limit using PIMMS. For this reason, we have assumed an interstellar absorbtion column density of 3.81×10^{21} cm^{-2} (as estimated by the Nh Heasarc Tool) and a power law spectrum with indices Γ varying in the range 1.5 and 2.5. For the MOS 1 instrument the previously quoted count rates correspond to unabsorbed fluxes of 9.10×10^{-15} erg cm^{-2} s^{-1} ($\Gamma = 1.5$) and 1.20×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 2.5$). For the MOS 2 instrument we get the unabsorbed fluxes of 1.12×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 1.5$) and 1.45×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 2.5$). For EPIC-PN we find 1.03×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 1.5$) and 1.28×10^{-14} erg cm^{-2} s^{-1} ($\Gamma = 2.5$), respectively. Therefore, we can set an upper limit for the flux from the putative source in the range 9.10×10^{-15}–1.45×10^{-14} erg cm^{-2} s^{-1}.

5. Discussion and conclusions

MACHO-96-BLG-5 is a microlensing observed event towards the bulge of the Galaxy with the exceptionally long duration of $\sim$ 970 days[4]. The measure of the parallax angle (Bennett et al. 2002) made it possible to estimate both the lens mass ($M = 6^{+10}_{-3}$ M$_{\odot}$) and its distance d from Earth (0.5–2 kpc).

Since the observed upper limits on the absolute brightness of main-sequence stars for this lens is $< 1\ L_{\odot}$, MACHO-96-BLG-5 is a BH candidate. If it is so, then the BH would accrete by interstellar medium (via the Bondi-Hoyle mechanism) thereby emitting X rays. Here, we have reported about a deep *XMM* observation in the $0.2 - 10$ keV band towards MACHO-96-BLG-5 lens position. The analysis of the observations (see Section 4) did not show any obvious source and it is consistent with a non-detection of the source. However, it is possible to estimate an upper limit on the source luminosity, which turns out to be in the range 9.10×10^{-15}– 1.45×10^{-14} erg cm^{-2} s^{-1}, depending on the power law index Γ.

This upper limit allows to constrain the accretion parameters of the BH candidate from a parametric study involving eqs. (3) and (4). In the BH mass-distance plane given in Figure 4, the curved line corresponds to the mass-distance relation (also given in Figure 1). This means that our BH candidate should lie on this curve (if its transverse velocity is $\simeq 30$ km s^{-1}) and within the two dotted vertical lines. The three oblique lines correspond to the X-ray upper limit of 9.10×10^{-15} erg cm^{-2} s^{-1} for three different values of the scale flux (F_s, $10^{-1}F_s$ and $10^{-2}F_s$). Obviously, varying F_s, it means that the accretion parameters (ϵ, ρ_{∞} and v) are changing. Thus, the region below the line labeled F_s corresponds to $F_X < 9.10 \times 10^{-15}$ erg cm^{-2} s^{-1}. The same holds for the regions below the other two lines. It is noticing that a BH accreting with $\rho_{\infty} \simeq 8.35 \times 10^{-25}$ g cm^{-3}, $\epsilon = 0.1$ and $v \simeq 30$ km s^{-1} (implying $F_s \simeq 4.45 \times 10^{-15}$ erg cm^{-2} s^{-1}), is inconsistent with the best fit values (mass and distance) for the MACHO-96-BLG-5 lens candidate. However, for a less efficient Bondi accretion ($\epsilon \simeq 10^{-5} - 10^{-3}$) the regions below the other two oblique lines show that the agreement is recovered.

[4]We also mention that recently Poindexter et al. (2005) presented the best fit solution for geocentric timescale for the same microlensing event and found that the event duration is 546 ± 165 days or 698 ± 303 days. This analysis leads to the conclusion that the lens of MACHO-96-BLG-5 is BH with a probability of about 37%.

Finally, it could be interesting to estimate the BH radiative efficiency $\eta = L_X/L_{Edd}$ with respect to the maximum allowed BH accretion rate given by the Eddington luminosity $L_{Edd} \simeq 1.38 \times 10^{38}(M/M_{\odot})$ erg s^{-1}. By using the BH mass and distance ranges, namely $3 < M < 16$ M$_{\odot}$ and $0.5 < d < 2$ kpc, we can compare the Eddington luminosity with the X-ray luminosity given by $L_X = F_X 4\pi d^2$ expected for MACHO-96-BLG-5. This procedure gives η in the range $1.2\times10^{-10} - 2.7\times10^{-9}$, in agreement with the efficiency estimates for BH accretion in quiescent galaxies and ultra-low luminous AGNs for which $\eta = 4\times10^{-12}$- 6×10^{-7} (Baganoff et al. 2003).

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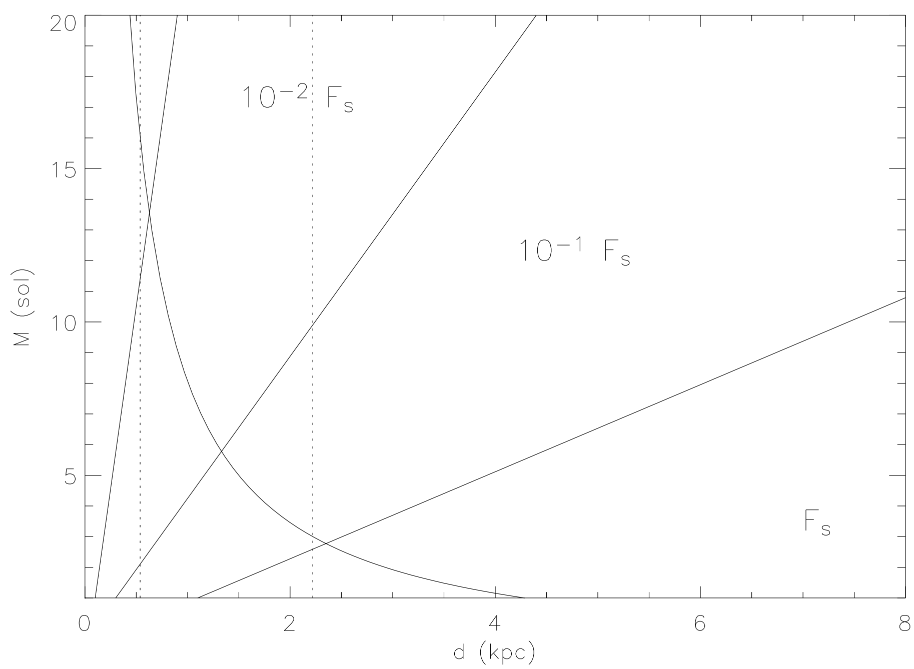

Fig. 4.— In the mass-distance plane (see Figure 1), the three oblique lines define the regions (below each line) where the X-ray flux due to the Bondi accretion is below the upper limit flux of 9.10×10^{-15} erg cm^{-2} s^{-1}.

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